A universe in which life as we know it could not exist. [For example, if the difference in mass between a proton and a neutron were zero, or less than the mass of the electron,  $0.511 \text{ MeV}/c^2$ , there would be no atoms: electrons would be captured by protons to make neutrons.] Such results have contributed to a philosophical idea called the **anthropic principle**, which says that if the universe were even a little different than it is, we could not be here. We physicists are trying to find out if there are some undiscovered fundamental laws that determined those conditions that allowed us to exist. A poet might say that the universe is exquisitely tuned, almost as if to accommodate us.

## Summary

The night sky contains myriads of stars including those in the Milky Way, which is a "side view" of our **Galaxy** looking along the plane of the disk. Our Galaxy includes over  $10^{11}$  stars. Beyond our Galaxy are billions of other galaxies.

Astronomical distances are measured in **light-years**  $(1 \text{ ly} \approx 10^{13} \text{ km})$ . The nearest star is about 4 ly away and the nearest large galaxy is 2 million ly away. Our Galactic disk has a diameter of about 100,000 ly. [Distances are sometimes specified in **parsecs**, where 1 parsec = 3.26 ly.]

Stars are believed to begin life as collapsing masses of gas (protostars), largely hydrogen. As they contract, they heat up (potential energy is transformed to kinetic energy). When the temperature reaches about 10 million degrees, nuclear fusion begins and forms heavier elements (**nucleosynthesis**), mainly helium at first. The energy released during these reactions heats the gas so its outward pressure balances the inward gravitational force, and the young star stabilizes as a **main-sequence** star. The tremendous luminosity of stars comes from the energy released during these thermonuclear reactions. After billions of years, as helium is collected in the core and hydrogen is used up, the core contracts and heats further. The outer envelope expands and cools, and the star becomes a **red giant** (larger diameter, redder color).

The next stage of stellar evolution depends on the mass of the star, which may have lost much of its original mass as its outer envelope escaped into space. Stars of residual mass less than about 1.4 solar masses cool further and become **white dwarfs**, eventually fading and going out altogether. Heavier stars contract further due to their greater gravity: the density approaches nuclear density, the huge pressure forces electrons to combine with protons to form neutrons, and the star becomes essentially a huge nucleus of neutrons. This is a **neutron star**, and the energy released during its final core collapse is believed to produce **supernova** explosions. If the star is very massive, it may contract even further and form a **black hole**, which is so dense that no matter or light can escape from it.

In the **general theory of relativity**, the **equivalence principle** states that an observer cannot distinguish acceleration from a gravitational field. Said another way, gravitational and inertial masses are the same. The theory predicts gravitational bending of light rays to a degree consistent with experiment. Gravity is treated as a curvature in space and time, the curvature being greater near massive objects. The universe as a whole may be curved. With sufficient mass, the curvature of the universe would be positive, and the universe is *closed* and *finite*; otherwise, it would be *open* and *infinite*. Today we believe the universe is **flat**.

Distant galaxies display a **redshift** in their spectral lines, originally interpreted as a Doppler shift. The universe is observed to be **expanding**, its galaxies racing away from each other at speeds (v) proportional to the distance (d) between them:

$$v = H_0 d, \qquad (33-4)$$

which is known as **Hubble's law** ( $H_0$  is the **Hubble parameter**). This expansion of the universe suggests an explosive origin, the **Big Bang**, which occurred about 13.8 billion years ago. It is not like an ordinary explosion, but rather an expansion of space itself.

The **cosmological principle** assumes that the universe, on a large scale, is homogeneous and isotropic.

Important evidence for the Big Bang model of the universe was the discovery of the **cosmic microwave background** radiation (CMB), which conforms to a blackbody radiation curve at a temperature of 2.725 K.

The Standard Model of the Big Bang provides a possible scenario as to how the universe developed as it expanded and cooled after the Big Bang. Starting at  $10^{-43}$  seconds after the Big Bang, according to this model, the universe underwent a brief but rapid exponential expansion, referred to as inflation. Shortly thereafter, quarks were confined into hadrons (the **hadron era**). About  $10^{-4}$  s after the Big Bang, the majority of hadrons disappeared, having combined with anti-hadrons, producing photons, leptons, and energy, leaving mainly photons and leptons to freely move, thus introducing the lepton era. By the time the universe was about 10 s old, the electrons too had mostly disappeared, having combined with their antiparticles; the universe was radiation-dominated. A couple of minutes later, nucleosynthesis began, but lasted only a few minutes. It then took almost four hundred thousand years before the universe was cool enough for electrons to combine with nuclei to form atoms (recombination). Photons, up to then continually being scattered off of free electrons, could now move freelythey were **decoupled** from matter and the universe became transparent. The background radiation had expanded and cooled so much that its total energy became less than the energy in matter, and matter dominated increasingly over radiation. Then stars and galaxies formed, producing a universe not much different than it is today-some 14 billion years later.

Recent observations indicate that the universe is essentially flat, that it contains an as-yet unknown type of **dark matter**, and that it is dominated by a mysterious **dark energy** which exerts a sort of negative gravity causing the expansion of the universe to accelerate. The total contributions of baryonic (normal) matter, dark matter, and dark energy sum up to the **critical density**.